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The origin of the strings in the outer regions of η Carinae

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ABSTRACT

The narrow optical filaments ('strings' or 'spikes') emerging from the Homunculus of η Carinae are modelled as resulting from the passage of ballistic 'bullets' of material through the dense circumstellar environment. In this explanation, the string is the decelerating flow of ablated gas from the bullet. An archive HST image and new forbidden line profiles of the most distinct of the strings are presented and discussed in terms of this simple model.

Key words: Stars: evolution – Stars: individual: η Carinae – Stars: mass-loss – ISM: bubbles; jets and outflows

1 INTRODUCTION

A recent addition to the wealth of physical features associated with the Luminous Blue Variable star η Carinae are the remarkable high speed filaments protruding radially from the Homunculus and visible in deep H α and [N II] λ6584 Å imagery (Meaburn, Wolstencroft & Walsh 1987, Meaburn et al. 1996). These features (which are variously referred to as 'spikes' - Meaburn et al. 1996; 'whiskers' - Morse et al. 1998; or 'strings' - Weis, Duschl & Chu (1999); we will use strings) are observed to extend out into the surrounding nebulosity.

Weis et al. (1999) have summarised the known properties of these strings, of which 5 are visible in HST images. They are typically $2-5\times10^{17}$ cm long and 6×10^{15} cm wide, tapering somewhat towards the tip. This length to width ratio of between 30-100 marks them as highly collimated structures. The strings point directly back to η Carinae. They are not perfectly straight however as some localised kinks and brightness knots are seen in some of the strings.

The velocity structures of the strings are no less remarkable than their optical morphologies. Meaburn et al. (1996) using the EMMI spectrometer on the New Technology Telescope (La Silla) found that, along the length of the most prominent string (String 1), the radial velocity changes from ~ -630 km s^{-1} to up to ~ -850 km s^{-1} at the discernable tip of the string (the systemic heliocentric radial velocity of η Carinae $V_{\rm sys} = 7$ km s^{-1}). Weis et al. (1999) were subsequently able to show that this velocity change is in fact linear with distance.

In this paper, new line profiles from the most prominent string are presented and compared with a previously published position-velocity array of line profiles from the area where the string emerges from the Homunculus. Various possible explanations are considered for the strings and a model of the strings based upon a dense bullet of material ploughing through the circumstellar environment of η Carinae is developed.

2 OBSERVATIONS

The HST archive [N II] λ6584 Å image of String 1 in Fig. 1 is one where the HST diffraction spikes generated by η Carinae are conveniently displaced so that the string is clearly visible. Note, however, that due to the extreme radial velocities of the strings some emission can be lost due to the narrow bandwidth of some of the HST filters (see Meaburn et al. 1996 and Weis et al. 1999 for a full discussion and complete set of images of the strings). The position/velocity (pv) array of [N II] λ6584 Å line profiles (see Meaburn et al. 1987 for details) in Fig. 2 is from the east/west slit length intersecting position A 12″ south of η Carinae, where String 1 emerges from the inner circumstellar shell that surrounds the Homunculus. The [N II] λ6584 Å and Hα line profiles in Figs. 3 a & b are from positions B and C respectively (see Fig. 1) along String 1 (see Meaburn et al. 1996 for the technical details). These have been extracted from the longslit pv arrays and corrected for the emission from adjacent regions along the slit length. The very high radial velocities of these features can cause contamination from nearby spectral lines. The different spectral lines displayed for the two positions were chosen to avoid this.

It can be seen in the pv array in Fig. 2 that the base of String 1 at A coincides closely with a remarkable spatially localised velocity feature that extends from $V_{\rm hel} = -800$ km s^{-1} (at the bottom of the figure) to $V_{\rm sys}$. This large range of velocities over indicates that the region at which the string emerges from the inner shell of η Carinae is highly disturbed.

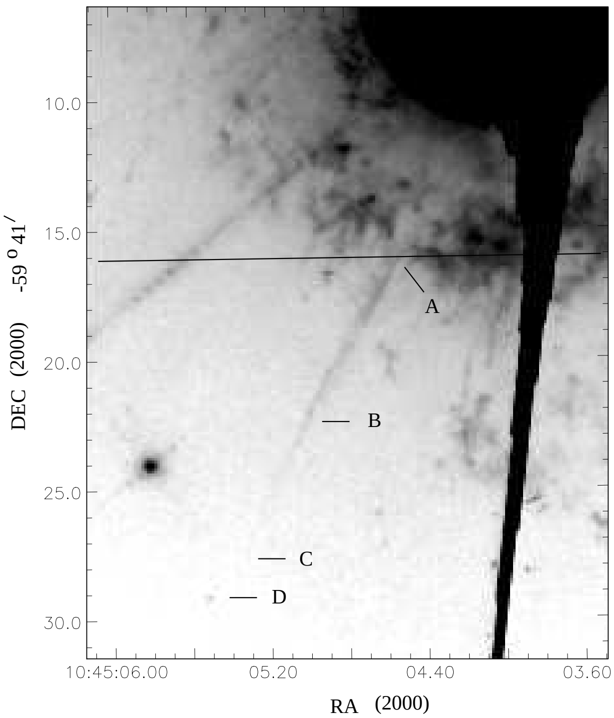

Figure 1. HST archive image of String 1 in the light of [N ii] λ6584 Å. The slit positions of Meaburn et al. 1996 are labelled and discussed in the text. The overexposed region at the top of the figure is the Homunculus with η Carinae itself lying beyond the top right corner of the image.

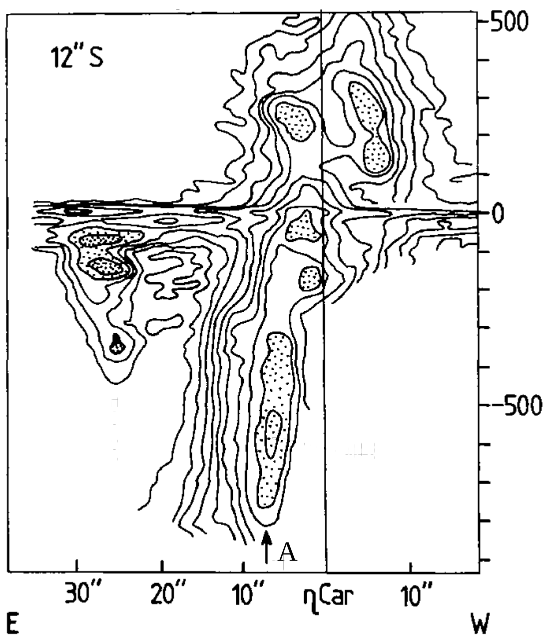

Figure 2. Position velocity arrays of line profiles obtained from the slit position that passes through point A, marked in Figure 1. The label 'η Car' marks the point of the slit immediately due south of η Carinae.

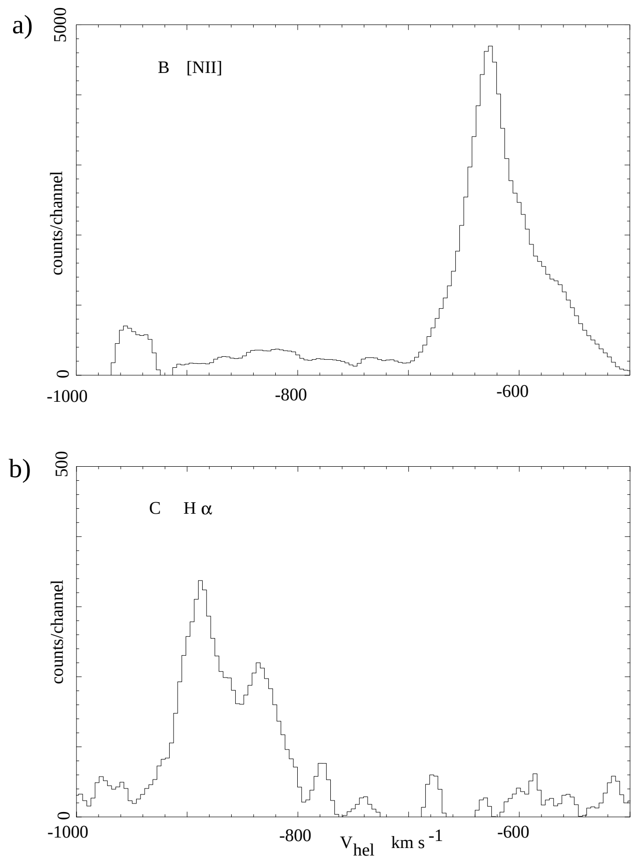

Figure 3. An [N ii] λ6584 Å and an Hα line profile from (a) position B and (b) position C respectively

The profiles from String 1 at positions C and B (Fig. 3 a & b) are easier to interpret. Profile C is clearly split by ≈ 48 km s^{-1} while profile B seems to consist of two blended components of comparable separation. These imply that the string is expanding at 24 km s^{-1} perpendicularly to the length of the string. However, the centroid of the split from position B is shifted by –600 km s^{-1} from $V_{\rm sys}$ while that from position C is shifted by –860 km s^{-1}. Positions B and C are at 21″ and 27″ from η Carinae respectively so a reasonably linear change of radial velocity along the length of String 1 is indicated. Even with such large shifts in radial velocity the widths (FWHM) of the individual velocity components (corrected for the 12 km s^{-1} instrumental resolution) are only ≈ 40 km s^{-1}.

Note that there is an unresolved stellar-like feature (at D in Fig. 1) and, although somewhat detached, it is in line with String 1 and η Carinae. Currie et al. (2000b) have used proper motion measurements to show that this is a bullet travelling at a higher velocity than the rest of the string and is likely to be physically associated with the string. Their astrometric measurements suggest that the bullets are travelling at up to 3000 km s^{-1} i.e. around 1% of the speed of light. The angle of the string to the plane of sky is determined by comparison of the astrometric velocity measurements with radial velocity measurements to be 25^{o} (Currie et al. 2000b). This angle agrees with that estimated by Weis et al. (1999).

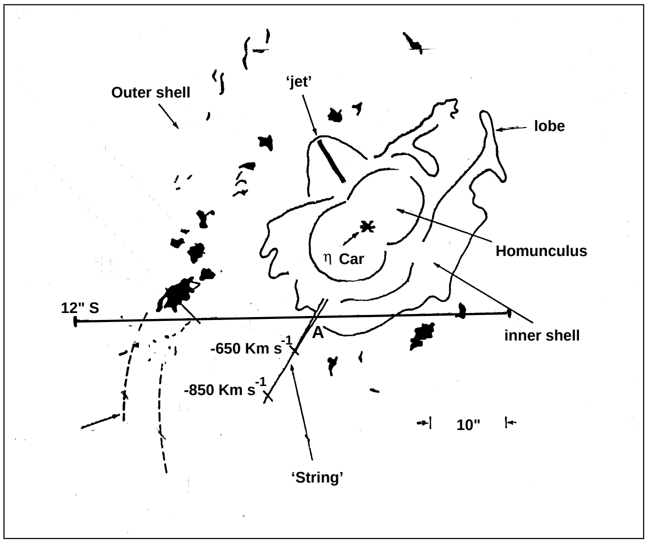

Figure 4. Sketch of the main features of the η Carinae nebulosity. The slit position marked is orientated exactly east-west

3 POSSIBLE EXPLANATIONS

In this section, various possible explanations for the origin of the strings are considered in turn. García-Segura et al. (1999) have shown that, for a planetary nebula medium in which the magnetic pressure dominates the gas pressure, narrow collimated jet like features with a velocity that increases along the jet can be produced. The calculations were two dimensional and they argued that when extended to 3D, pinching instabilities could lead to localised disturbances along the jet and possibly break up into clumps.

At first sight, this type of model, suitably adapted for the conditions in the η Carinae nebulosity, appears promising. A major problem is that a bipolar axis is required along which these structures will form. In η Carinae there are at least 5 strings. There are likely to be more since the observed strings happen to lie at fortuitous positions and face-on and obscured strings will not be detected. Some kind of precessing axis also appears unlikely since the dynamical times of the strings indicates that they were all ejected at the time of the great outburst of the 1840s although a rapidly precessing and tumbling axis cannot be ruled out.

The number of strings is also a problem for a hydrodynamical jet interpretation for similar reasons to those above. Several collimating sources with differing orientations are required and there is also the problem of the seemingly coincident temporal origin. Again, some kind of source that varied rapidly within η Carinae remains a possibility. It is also worth noting that there is an episodic jet emerging from the Homunculus (Meaburn et al. 1993) but it bears little similarity to the strings (it is much broader and brighter and has a single velocity). Amongst a list of suggestions, Weis et al. (1999) suggest that the strings could result from projection effects from larger funnels but as discussed here, generating numerous such funnels would require a jet and the only certain jet feature is not attended by strings.

In favourable circumstances, one could envisige gaps in a circumstellar shell allowing beams of emission to be formed as the radiation scatters off dust in the beam. Indeed, the striking infrared image of the Homunculus by Currie et al. (2000a) seems to show just this effect: the Homunculus appears covered in short spikes of emission. However, this is easily ruled out as a possible explanation for the optical strings here since the beams should be straight rather than kinked as observed.

The most likely explanation is one which involves the ejecta of the 1840s outburst (as concluded by Weis et al. 1999 and Currie et al. 2000b) since the ages of the strings and their distribution about the Homunculus is then accounted for. One of the possibilities listed by Weis et al. (1999) is that the strings could be a train of individual bullets following the same path. This cannot be firmly ruled out until higher resolution observations become available but there are problems with such an interpretation. The strings are of uniform kinematical age, so at an earlier time the bullets must have all been located at the same position and have been travelling in the same direction yet with a range of velocities. This could be the result if a large fragment of ejecta breaks up but the velocity and mass distribution of the resulting fragments must then be fairly uniform to allow the strings to remain coherent and recognisible. Furthermore, each fragment must retain the exact direction of motion of the original body as it breaks up. These constraints make it seem unlikely that the strings result from a train of bullets.

Soker (2001) has suggested that the strings are the result of ionization shadows behind dense clumps in the Homunculus. The surrounding gas is ionized and compresses the shadow gas which is then ionized sometime later, becoming visible as a string. The velocity structure of the strings is not accounted for by the model. The discovery of the high speed knots of emission beyond the tips of the strings (see Currie et al. 2000a) may cause problems for this model since this suggests that the strings may have been somehow generated behind a high velocity clump rather than through the more quiescent mechanism postulated by Soker (though the model may still be applicable to the filaments in NGC 5443).

Redman & Meaburn (2000) described a model for the strings in which the strings are generated by single bullets ploughing through the surrounding medium. The trails of material left behind as the bullet is disrupted are identified as the strings. We develop this model in the next section. Weis et al. (1999) included the possibility that the spikes could be generated by such a mechanism in their list of possible explanations.

4 A MODEL FOR THE STRINGS

We suggest that the strings are simply the effects of the passage of dense fragments of ejecta interacting with the circumstellar environment. Knots of supernova ejecta travelling at higher speeds than the edge of the supernova remnant have been found to lie beyond the main remnant body (e.g. Braun et al 1987). We suggest that a similar process operates in η Carinae so that the densest pieces of ejecta

will be slowed negligibly and overrun the main Homunculus body. The visible string is the trail left behind by the passage of the ejected fragment. In Dyson, Hartquist & Biro (1993) and subsequent papers the problem of the tail shape that results from an interaction between a clump and a flow has been studied in detail. However, Dyson, Hartquist & Biro (1993) are concerned with quasi-steady flows that can occur after the initial stages of the interaction of the clump and flow have settled down and so their results are probably not applicable here. Klein, McKee & Colella (1994) have carried out a detailed analytical and numerical study of the interaction between a small clump and a strong shock and they trace the evolution of the clump as it is hit by the shockwave, embedded in the post-shock flow and eventually destroyed. The timescale for the destruction of the clump is shorter than the time taken for a clump to sweep up a column density of material from the ISM because the knots are vulnerable to the growth of Kelvin-Helmholtz (K-H) instabilities when embedded in the post shock flow. Defining $\chi \equiv n_{\rm c}/n_{\rm i}$ as the density contrast between the clump and the ISM, with $n_{\rm c}$ and $n_{\rm i}$ being the clump and ISM densities respectively, the destruction time, $t_{\rm d}$, is then (Klein, McKee & Colella 1994)

$$t_{\rm d} = \chi \frac{r_{\rm c}}{V_{\rm s}}, \qquad (1)$$

where $V_{\rm s}$ is the shock speed. Applying this cloud destruction equation to the bullets from η Carinae, $V_{\rm s} \lesssim 1000$ km s^{-1} is used as an upper limit to the shock speed (the deprojected velocity of the highest speed string material - Section 1). The bullet radius is $r_{\rm c} \simeq 3 \times 10^{15}$ cm i.e. assuming the initial bullet radius to be approximately half that of the width of the trail (see below). Since the bullet appears to still survive, the destruction time $t_{\rm d}$ must be greater than 150 years. This gives that the density constrast between the clump and external medium should be $\chi \gtrsim 100$. Observationally, this requirement seems plausible. Kennicutt (1984) measured the density of the Carina nebula to be ~ 100 cm^{-3} towards the centre of the nebula. Morse et al. (1998) estimate that dusty clumps in the Homunculus have densities of $10^5 - 10^6$. They also measure the density of the strings to be 400 cm^{-3}. The strings have a length to width ratio of 30-100 so assuming the bullet to originally be comparable in diameter to the string, suggests an initial bullet density of a $\gtrsim 10^4$ cm^{-3}. It seems reasonable then to adopt a bullet density of 10^4 cm^{-3} and an ambient density of 10^2 cm^{-3}.

That the trail of material ablated from the bullet has not appreciably expanded is easily verified because the dynamical age of the trail is $t_{\rm dyn} \simeq 150$ yr (similar to that of the Homunculus) and even if the oldest parts of the tail had been expanding at the thermal sound speed of ionized gas ($c_{\rm i} = 10$ km s^{-1}) for this time they would only have swelled to

$$c_{\rm i} t_{\rm dyn} \lesssim 4.5 \times 10^{15} \text{ cm}, \qquad (2)$$

The distance to η Carinae used is 2.3 kpc (this is an unambiguous distance measurement - see Meaburn 1999). The expansion is less than the thickness of the strings of 6×10^{15} cm estimated by Weis et al. (1999), who also point out that there is little evidence that the string gets progressively thinner towards its tip. It is unlikely therefore that the clump had an initial diameter greater than the width of the string. Since the clump is detected in the HST images, it seems reasonable to adopt a clump diameter of the order of the thickness of the string.

Within the strings, localised knots of emission are seen in HST images. They do not appear to be any wider than the rest of the string. Weis et al. (1999) marginally resolve the velocity widths of the localised knots to be $\simeq 22$ km s^{-1} (in accord with our measurents in Section 2). If the clump is destroyed primarily by the development of K-H instabilities, the most disruptive modes are those with wavelengths of the order of the original clump radius. The embedded knots could then represent eddies in the tail generated by the K-H instability and the velocity widths would then be a measure of their internal turbulence. The slight deviations in the otherwise remarkably straight tails most likely result from the highly non-linear action of the disruption process.

The displacement of the bullet and strings (see Figure 1, and Currie et al. 2000b) has a straightforward explanation in terms of our simple model: the gas stripped from the ejecta fragment may be initially too hot to be optically visible and only once it has cooled somewhat downstream will it be detectable. The details of the shock-cloud interaction will be complicated but we envisage that a slow shock driving into the dense bullet gives rise to the optically visible [N II] λ6584 Å emission at the bullet surface while a fast bow shock between the heated gas expanding from the bullet surface and the incoming medium would heat this material to a high temperature. Some of the gas will be heated to $\gtrsim 10^6$K as it is exposed to a 1000 km s^{-1} shock but some portions of the shock surface will be oblique to the incoming flow, giving a range of post-shock temperatures.

The detailed formation of the string itself may be as follows. Hot postshock gas is stripped from the fast moving clump/bullet. The temperature of this gas depends on the very uncertain shock strength. It is likely to be in the range $10^5 - 10^6$ K. In order to produce optical emission, this gas must cool through UV resonance lines. The detection of O VI resonance lines would be a simple test that this cooling is occuring since this UV line indicates the presence of gas with a temperature of $\sim 10^5$K. Unfortunately, the ejecta is of low O abundance so this observation is unfeasible at present. The cooling rate of gas in the temperature range 5×10^4 K $- 5 \times 10^7$ K can be well approximated by (Kahn 1976)

$$\Lambda = 1.33 \times 10^{-19} T^{-1/2} \text{ erg cm}^3 \text{ s}^{-1}. \qquad (3)$$

Once the lower end of this temperature range is reached, the gas will primarily cool through optical forbidden lines. The narrow velocity widths of $\simeq 24$ km s^{-1} (Section 2) for the strings are indicitive of a local sound speed of ionized gas at a temperature of $\sim 10^4$ K.

If the standard shock results apply for the post shock density and pressure ($P_{\rm s} = 3/4 \rho_0 V_{\rm s}$; $\rho_{\rm s} = 4\rho_0$) the cooling time of the shocked bullet gas is (Kahn 1998)

$$t_{\rm cool} = \frac{P_{\rm s}^{3/2}}{q \rho_{\rm s}^{5/2}} = \left(\frac{3}{4}\right)^{3/2} \left(\frac{1}{32}\right) q^{-1} \rho_0^{-1} V_{\rm s}^3, \qquad (4)$$

where ρ_0 is the pre-shock density and q is a constant (see Kahn 1998).

Using the following illustrative values $V_{\rm s} \simeq 1000$ km s^{-1} (and this is an upper limit, as described above); $q \simeq 4 \times$

10^{32} cm^6 gm^{-1} s^{-4} and $\rho_0 \simeq 10^4 \times 2 \times 10^{-24}$ gm cm^{-3} the cooling time is then

$$t_{\rm cool} \lesssim 80 \text{ yrs.} \quad (5)$$

The displacement between the string and bullet is roughly 5 percent of the length of the string (see Fig 1). Since the string is 150 years old, a cooling time of ~ 10 yrs is required. Note that the shock velocity used is an estimated upper limit. The medium into which the strings are moving is likely to be flowing away from the star, which will reduce the velocity difference and hence shock strength (halving the shock velocity to 500 km s^{-1} is required to give a cooling time of $t_{\rm cool} \sim 10$ yrs). Given the highly uncertain shock speeds and densities this very simple model gives a very reasonable quantative agreement with the available observations.

Finally, the velocity structure of the strings may be accounted for as follows. Away from the head of the string, the material in the string will be moving at a different velocity than that of the neighbouring medium. There will be a gradual slowing of the edges of the string at the interface between the string gas and external medium. If this is a steady deceleration process, then clearly the older parts of the string will have been slowed more than those recently stripped from the bullet and the velocity along the string will therefore change in a linear fashion. The disturbed part of the inner shell at the base of the string (Fig 2, Section 2) may represent the effects of the bullet breaking through the inner regions of the nebula.

In the absence of measured values for many of the physical quantities, the model cannot be developed much further. Given the uncertainties, we suggest that our very simple model is a plausible explanation for the origin and structure of the strings.

5 CONCLUSIONS

We have suggested that the narrow, collimated strings emerging from the inner shell of η Carinae are due to the passage of dense fragments of ejecta through the circumstellar environment. We have argued that this very simple model is capable of broadly accounting for most of the observed features of the strings. The clump that formed the string is visble beyond the end of the string; the collimation of the string is due to both the high density contrast ($\gtrsim 100$) between the clump and the circumstellar environment and the high speed of the clump - the string has not had time to expand appreciably; the distance between the observed clump and string is due to the time required for the newly shocked ablated gas from the clump to cool and become optically visible; the linear change in velocity along the string is due simply to the gas in the string being further decelerated by the external environment.

This model could be developed further using the latest numerical hydrodynamic codes to model the complicated physics involved in the destruction of the ejecta fragments. While the η Carinae strings are presently unusual enough to warrant special explanation, it is entirely possible that they may turn out to be a common feature of new explosively generated circumstellar nebulosity.

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REFERENCES

Braun R., Gull S. F., Perley R. A., 1987, Nature, 327, 395
Currie D. et al., 2000a, ESO Messenger, 100, 12
Currie D., Le Mignant D., Svensson B., Tordo S., Bonaccini D., 2000b, ESO Messenger, 102, 25
Dyson J. E., Hartquist T. W., Biro S., 1993, MNRAS, 261, 430
García-Segura G., Langer N., Różyczka M., Franco J., 1999, ApJ, 517, 767
Kahn F. D., 1976, A&A, 50, 145
Kahn F. D., 1998, in Breitschwerdt D., Freyberg M. J., Trümper J., eds, The Local Bubble and Beyond - Lyman Spitzer Colloquium: Proc. IAU Col. 166. Springer, p. 483
Kennicutt R. C., 1984, ApJ, 287, 116
Klein R. I., McKee C. F., Colella P., 1994, ApJ, 420, 213
Meaburn J., Gehring G., Walsh J. A., Palmer J. W., López J. A., Bryce M., Raga A. C., 1993, A&A, 276, L21
Meaburn J., Boumis P., Walsh J. R., Steffen W., Holloway A. J., Williams R. J. R., Bryce M., 1996, MNRAS, 282, 1313
Meaburn J., Wolstencroft R. D., Walsh J. R., 1987, A&A, 181, 333
Meaburn J., 1999, in Morse J. A., Humphreys R. M., Daminelli A., eds, Eta Carinae at the Millennium. p. 89
Morse J. A., Davidson K., Bally J., Ebbets D., Balick B., Frank A., 1998, AJ, 116, 2443
Redman M. P., Meaburn J., 2000, in Gull T., Johansson S., Davidson K., eds, Eta Carinae and Other Mysterious stars. p. In press
Soker N., 2001, ApJ, 377, 672
Weis K., Duschl W. J., Chu Y. H., 1999, A&A, 349, 467